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A STUDY ON SOME TECHNIQUES FOR IMPROVING THERMO HYDRAULIC PERFORMANCE OF A SOLAR AIR HEATER

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ABSTRACT

Artificial roughness is used in solar air heater absorber plate to break laminar boundary sub layer. It enhances rate of heat transfer from the absorber plate to the over flowing air stream. Various roughness geometries have been designed to study thermo hydraulic performance of black coated metallic (Al alloy) absorbers under standard testing condition. They are namely two pass sine wave corrugated absorber, hemispherical protruded and pin fin absorbers. The different geometrical parameters such as height of roughness element, long way and short way length, hydraulic diameter, etc. were studied by standardized procedures. Their effects on overall on performance of solar air heater have also been highlighted. It was observed that pin fin absorber gave best thermal performance following hemispherical protruded and sine wave absorber. Collector heat gain factor based on outlet temperature for different absorber reveals pin fin to be the best choice. Corrugated sine wave absorber gave best hydraulic performance following protruded and pin fin absorber. Variation of Reynolds number with Nusselt number, friction factor for different geometrical parameters such as hydraulic diameter, pitch, and roughness height has also been studied.

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Keywords: Solar air heater, Efficiency, Heat removal factor, Artificial roughness.

1. INTRODUCTION

In the present scenario of depleting fossil fuels, the value of renewable, sustainable and non-polluting sources of energy has received a great deal of interest. Amongst these it is solar energy, which is the biggest source of renewable energy. One way to utilize this diffuse solar radiation is through different black coated solar thermal collectors to enhance the temperature incoming fluid. Solar air heater (SAH) is one such collector which may be readily built at a reasonably lower cost.

A solar air heater can be defined as a solar thermal energy conversion device. It is essentially a flat plate collector with an absorber plate, a transparent cover system at the top, insulations at the bottom and on all four sides. The whole assembly is encased in a sheet metal container. The working fluid is air, though the passage and its flow directions may vary according to the type of air heater.

Solar air heater can be classified into porous and non-porous types depending on the type of the absorber plate. Depending on the number of passes, SAH can be classified into single pass and double pass [1].

Solar air heaters are very useful because of the fact that they are easier to build, there is no problem due to the leakage of air, there is no fear of freezing of the working fluid and there is no chance of corrosion in the heat transferring surfaces.

The greatest drawback of SAH is that it has low efficiency because of the fact that air is a very bad conductor of heat. As a result, the amount of heat absorbed by the flowing air from the surface of the absorber plate is very low. Thus, various steps have been investigated to increase the transfer of heat from the absorber plate to the mass of flowing air by increasing the convective heat transfer coefficient between air and the absorber plate. Two distinct methods to enhance heat transfer from black coated absorber are; (1) Use of artificially roughened absorber plates in SAH. (2) By increasing the area of heat transfer with the use of corrugated or extended surfaces, without affecting the heat transfer coefficient. The aim of the artificial roughness is to create turbulence at the laminar boundary sub- layer to increase the mixing by the formation of eddies and vortices. But the turbulence must be created very near to the laminar sub-layer so that the pumping work required by the blower is not increased substantially. It has been observed that along with the heat transfer coefficient, the friction factor is also increased due to the presence of roughness geometry. Thus, it is obvious that to completely evaluate the performance of a SAH, both the heat collection rate and pumping power should be taken into account. This is known as the thermo hydraulic efficiency of the SAH.

2. LITERATURE REVIEW

Extensive work has been reported in literature on solar air heaters. Many authors have reported their findings on the investigations done on forced convective heat transfer in smooth and roughened solar absorber ducts.

Artificial roughness on the surface of the absorber plate can be provided by the means of small diameter wire, v-ribs, wire mesh, etc. and by forming dimple or protrusion shape geometry as has been reported by Varun et al. [2]. Correlations for Nusselt number and friction factor for SAH absorber plate with hemispherical protrusions as artificial roughness was studied. It has been observed from experiments that protruded absorber plate results in higher heat transfer coefficient as compared to smooth plate at an added friction penalty. Maximum enhancement of Nusselt number and friction factor has been found to be 3.8 and 2.2 times respectively in comparison to smooth duct for the investigated range of parameters. Again, under a given set of operating conditions, Nusselt number has been found to be a function of relative short way length, relative long way length and relative print diameter. For given values of roughness parameters, Nusselt number increases monotonously with an increase of Reynolds number. Protrusion geometries are also advantageous as they don’t add to the weight of the absorber [3]. Some authors such as Peng et al. [4] and Ho et al. [5] had investigated the effect of pin-type and internal fins on the heat transfer coefficient. It had been found that the presence of fins greatly increased the heat transfer coefficient of air and could reach thrice that of flat plate collector. Artificial roughness in the form of repeated ribs had also been investigated by several authors. Ribs are also a very desirable method as they enhance heat transfer coefficient without increasing the friction losses. Hans et al. [6] used multiple v-ribs along the width of heat exchanging surface of a solar air heater to create artificial roughness for heat transfer enhancement.

3. MATERIALS AND METHODS

3.1 Experimental setup and development

An experimental set-up was designed and fabricated to carry out the experimental investigation on heat transfer and flow characteristics of artificially roughened duct used in different solar air heaters. A rectangular duct with an aspect ratio of 10, measuring $2400 \times 375 \times 37.5\ mm^3$ was fabricated in accordance with established standards [7]. The SAH enclosure was 2438 mm in length, 890 mm in width and 100 mm in height and made of aluminum angle, flat and sheet to reduce its weight and also to increase rate of heat transfer since aluminum is good conductor of heat [8]. A blackened sheet of aluminum alloy of dimension $2400 \times 870 \times 1.5\ mm^3$ was used as the absorber plate. Wood, thermocol, mild steel, etc. were the other raw materials used for the purpose of insulations, solar air heater holding frame, etc. Rubber gasket of appropriate size was used in between frame and glazing materials such as for holding the system air tight. Two centrifugal blowers of 450 W and capacity of $2.5\ m^3\ min^{-1}$ with two converging aluminum cones were used for pumping the ambient air through the rectangular duct. The heat gained from solar radiation is transferred convectively to the air stream entering from the bottom and flowing upwards across the absorber. Some other important components used are glass slab, transparent PVC plate, Al cover sheet. The M.S. frame built for supporting and changing the angle of incidence of sunlight according to the seasons over years. It was built using M.S. angles, M.S. flat and M.S. rod of different dimensions and sizes to erect solar air heater in appropriate orientation with respect to solar radiation.

The temperature rises of air during the experiments were measured using sixteen thermocouples (PT-100) arranged over the path of air flow with digital display unit over the entire experimental duration. The pressure drop in the SAH between the air at inlet and the air at outlet was measured using inclined U-tube manometer. The velocity of the fluid flow and hence the mass flow rate of air was measured using Pitot tube. The different aluminum absorbers designed and experimented have been briefly discussed below.

3.2 Hemispherical protrusion assembly

The array of hemispherical protrusion consisted of hemispheres of 5 mm diameter and protrusion height (3-5) mm developed in house [8]. The hemispherical protrusions were produced using a hemispherical die and punch attachment in conventional radial drilling machine available in University Central Workshop, The hemispherical protrusions were in staggered formation with parameters as given in Table 1. The detail diagrams of the hemispherical protrusion have been presented in Fig.1 and Fig. 2 depicting short way length (S) and long way length (L) with protrusion diameter (d) and protrusion height (e).

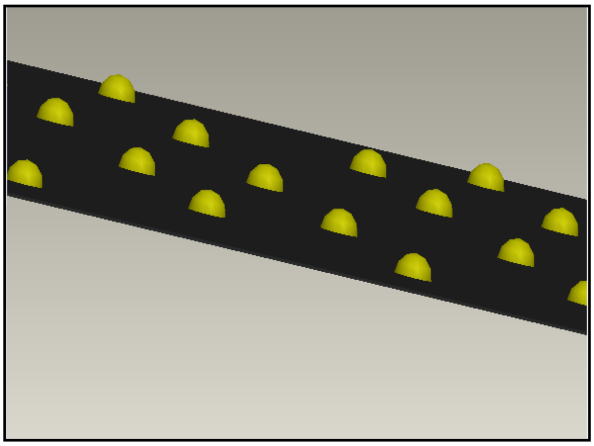

Fig.1 Hemispherical protruded solar energy absorber

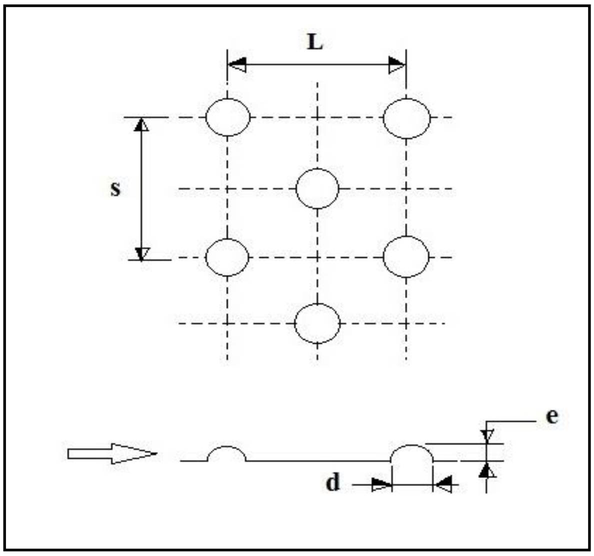

Fig.2 Long way and short way length of absorber

3.3 Pin fin assembly

The pin fin assembly used in the present investigation is consisted of commercially available aluminum rivets of 5 mm diameter and 25 mm in length. The fins are in in-line arrangement with a pitch of 15 mm. The absorber plate has been drilled in appropriate locations and then the 5 mm diameter rivets were pressed fitted inside the drill hole. The flat aluminum absorber constitutes the base plate for the pin fin array. The final arrays of riveted assembly plate give rise to the aluminum pin finned solar energy absorber. The different view of the pin finned solar energy absorber has been presented in Fig.3 below.

The direction of air flow is perpendicular to the length of the pin fin. It is in line with the natural convection driven by buoyancy to increase thermal performance. The temperature rise of the air was measured with pre-calibrated thermocouples which were shielded from direct solar radiation to increase accuracy of the readings

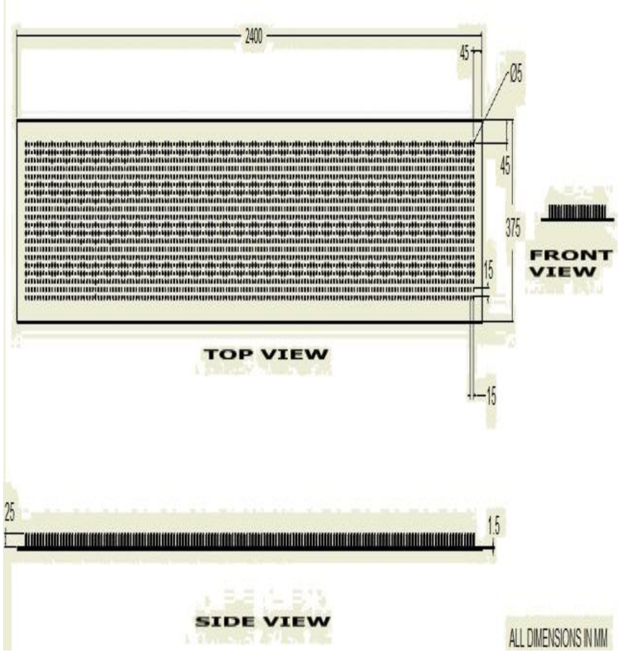

Fig.3. Absorber plate with pin fins

3.4 Sine wave corrugated absorber assembly

The net size of the corrugated aluminum foil is 2350 mm × 370 mm × 1 mm. The foil was black coated to increase its absorptance to solar radiation. The photographic view of the black coated aluminum plate and air heater assembly is shown in the Fig. 4. The absorber foil is light in weight, corrosion resistant and has better heat transfer capacity than that of the conventional steel foil. The alloy is composed of proportionate amount of allying material other than aluminum as base material. Various parameters of the foil are as listed below: The pitch (p = 75 mm) and height of corrugation (e) = 25 mm. Appropriate die and punch were developed to impart the sine wave corrugation for the absorber. Fig.4 and Fig.5 show the profile of corrugated solar air heater.

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Fig.4 Sine wave corrugated solar air heater

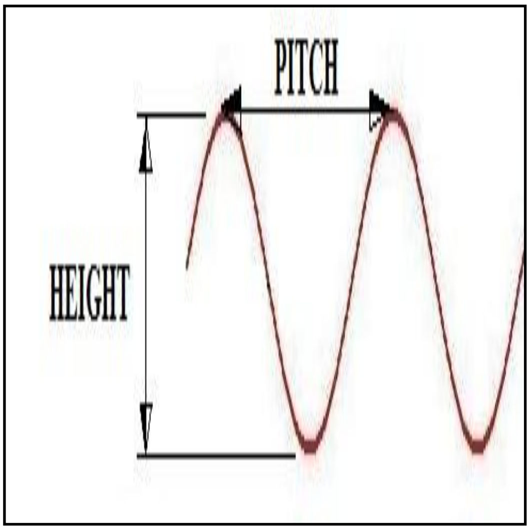

Fig.5 Profile of corrugated absorber

3.5 Mathematical modeling

To analyze the performance of three different type solar air absorbers, the following assumptions are considered to simplify the analysis.
(1) The temperature difference between the plate and fins is neglected due to the large thermal conductivity of the absorber plate and pin-fins.
(2) The thermal process in roughened air collector is approximately in steady state.
(3) Centrifugal pump causes negligible rise in air temperature.
(4) The glazing material has negligible heat capacity.

3.5.1 Heat balance model for the collector

According to the assumptions made on the physical model, the heat balance of the solar collector can be given as:

$$Q_s(\tau\alpha) = I_c F(\tau\alpha) = Q_u + Q_{cl} \qquad (1)$$

Hest loss of collector Q_{cl} is given by:

$$Q_{cl} = FU_{cl}\left(T_p - T_a\right) \qquad (2)$$

where

$$U_{cl} = U_b + U_s + U_t \qquad (3)$$

Again,

$$Q_u = \dot{m}C_p(T_o - T_i) = I_c F(\tau\alpha) - FU_{cl}(T_p - T_a) \qquad (4)$$

Therefore

$$\begin{aligned}\eta &= \frac{Q_u}{Q_s} = (\tau\alpha) - U_{cl}\frac{T_p - T_a}{I_c} \\ &= F_R\left[(\tau\alpha) - U_{cl}\frac{T_i - T_a}{I_c}\right] \\ &= A - B\frac{T_i - T_a}{I_c} \qquad (5)\end{aligned}$$

But for conventional solar air heater Eq. (5) cannot be used since T_i is approximately equal to T_a.. Therefore the above equation may be modified on the basis of collector heat gain factor (F_o) relating to air exit temperature [9].

$$\eta = F_0\left[(\tau\alpha) - U_{cl}\frac{T_0 - T_a}{I_c}\right] \qquad (6)$$

3.5.2 Thermo hydraulic performance of solar air heaters

The thermal efficiency of a solar air heater increases with increase in mass flow rate and with higher mass flow rate, friction losses becomes higher. This increases the energy expenditure required to propel the air through the collector. Thus it is necessary to consider the energy expenditure in the blower along with the useful energy gain. Cortes and Piacentini [10], Gupta et al. [11] and Gupta [12] proposed "effective efficiency", η_{eff} as:

$$\eta_{eff} = (q_u - \frac{P_m}{c})IA_p \qquad (7)$$

Where c is the conversion factor to account for the conversion of high grade mechanical energy to thermal energy and it is given by:

$$c = \eta_F\eta_m\eta_{tr}\eta_{th} \qquad (7a)$$

Where η_F is the efficiency of the fan, η_m is efficiency of the motor, η_{tr} is the efficiency of the electric transmission from the power supply, and η_{th} is the efficiency of thermal conversion of the power plant.

The rate of useful thermal energy may be obtained from the equation:

$$q_u = F'\left[I(\tau\alpha) - \frac{U_L(t_o - t_i)}{2}\right]A_p \qquad (8)$$

Where,

$$F' = \frac{h}{(h + U_L)} \qquad . \qquad (9)$$

The rate of useful energy gain of a solar air heater with artificial roughness may also be calculated by using the Eq. (10).

$$q_u = hA_p(t_{pm} - t_{fm}) \qquad (10)$$

or

$$q_u = mC_p(t_o - t_i) \qquad (11)$$

The mechanical power consumed is given by the Eq. (12)

$$P_m = \mathrm{VA\Delta P} \qquad (12)$$

Where

$$\Delta P = \frac{2fLV^2\rho}{D} \tag{13}$$

Therefore,

$$\begin{aligned} P_m &= \frac{VA2fL_cV^2\rho}{D} \\ &= V(WH)2fL_cV^2\rho/[\frac{2WH}{W+H}] \\ &= \rho f L_c V^3 (W+H) \end{aligned} \tag{14}$$

For artificially roughened solar air heaters friction factor f with mentioned geometry is given by the Eq. (15) [3].

$$f = 0.1911(\frac{e}{D})^{0.196}(\frac{W}{H})^{-0.093} (Re)^{-0.165}\exp[-0.993(1-\beta/70)^2] \tag{15}$$

Substituting for power consumption, P_m , from Eq. (14), and for the rate of useful energy gain, q_u , from Eq. (11), into Eq. (1), the effective efficiency of a solar air heater can be calculated as:

$$\begin{aligned} \eta_{eff} &= \{F[I(\tau\alpha) - U_L(t_o - t_i)/2]A_p \\ &\quad -\rho f L_c V^3 (W+H)/c\}/IA_p \end{aligned} \tag{16}$$

Equation (10) can also be used for determination of effective efficiency for a solar air heater with smooth absorber plate. The friction factor and heat transfer co-efficient for a solar air heater with a smooth absorber plate may be obtained from the Blasius and the Dittus-Boelter equations [13], respectively as:

$$f_s = 0.079(Re)^{-0.25} \tag{17}$$

$$h_s = 0.023\left(\frac{k}{D}\right)(Re)^{0.8}(\Pr)^{0.6} \tag{18}$$

Thus for a solar air heater with smooth absorber plate:

$$F_s = \frac{h_s}{h_s + U_L} \tag{19}$$

$$\eta_{eff} = \frac{\left\{F_s'\left[I(\tau\alpha) - \frac{U_L(t_0 - t_i)_s}{2}\right]A_p - \frac{\rho f_s L V^3 (W+H)}{c}\right\}}{IA_p} \tag{20}$$

The pressure loss due to flow through the pin-fin array is represented by a friction factor (*f*), based on the Darcy's relationship and it can be rewritten as:

$$f = \frac{2\Delta P}{(L_c/d_f)\left(\frac{m}{A_{ff}}\right)^2 (1/\rho)} \tag{21}$$

Where

$$A_{ff} = W(H+C) - N_x h_f d \tag{22}$$

as considered by Karthikeyan and Rathnasamy [14].

The values of the efficiency were computed for a set of system and operating parameters (absorber plate with different roughness geometry such as pinned fin, hemispherical protruded and sine wave corrugated, relative roughness height, mass flow rate) for a given duct geometry.

4. RESULTS AND DISCUSSIONS

The range of system and operating parameters used in the present experimental investigation for the different absorber roughness geometries are listed in Table 1, Table 2 and Table 3. Some similar parameters were used for the design calculation and testing of the different SAH system and it has been taken from the results published by Bhushan and Singh [3], Peng et al.[4] and Hans et al. [6]. These geometrical parameters are exclusively chosen for these three solar absorbers.

Table 1: Designed parameters for hemispherical protrusions

Quantity	**Formula**	**Values obtained**
Relative short way length	$\frac{S}{e}$	15
Relative long way length	$\frac{L}{e}$	20
Relative print diameter	$\frac{d}{D}$	0.15
Relative roughness height	$\frac{e}{D}$	0.04
Duct aspect ratio	$\frac{W}{H}$	10

Table 2 Designed parameters for pin fin

Quantity	**Formula**	**Values obtained**
Dimensionless pin-fin span	$\frac{S}{d_f}$	3
Dimensionless pin-fin height	$\frac{h_f}{d_f}$	5
Relative height	$\frac{d_f}{D}$	0.07
Duct aspect ratio	$\frac{W}{H}$	10

Table 3: Designed parameters for sine wave

Quantity	**Formula**	**Values obtained**
Relative short way length	$\frac{S}{e}$	3

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Relative long way length	$\frac{L}{e}$	3
Relative print diameter	$\frac{d}{D}$	0.15
Relative roughness height	$\frac{e}{D}$	0.04
Duct aspect ratio	$\frac{W}{H}$	10

The thermal performance of solar air heater depends on intensity of solar radiation, design parameters such as thickness of insulation, number and types of glass cover, number of passes, glazing and absorber materials, geometry and orientation of absorber, weather and operating conditions, etc. The collector performance tests were conducted on sunny and clear sky days in Tezpur University campus in the months of May, June 2012. The inclination of the collector was adjusted to 26 ° to incident maximum solar radiation. Three air mass flow rate of 0.0208, 0.0313 and 0.0417 kg/s were maintained to find the performance of solar air absorbers. The average solar energy available in the months of May, June was 650 W/m^2 and highest value is expected at noon (11.30 a.m.). The inlet air temperature is similar to ambient air in the range of (32-36) °C. It was also observed that highest temperature rise occurred at the period of 10.30- 12.30) p.m. The maximum temperature rise 38 °C was seen for pin fin absorber and minimum for corrugated sine wave absorber (28 °C).

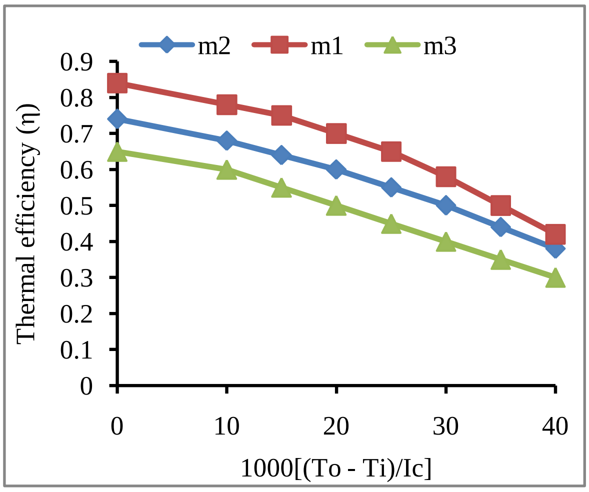

Fig. 6 Variations of collector efficiency with temperature parameter for pin fin absorber.

The computation for collector efficiency was done for incident of solar radiations measured from 10 a.m. to 1 p.m. Collector efficiency versus the temperature parameter $(T_o - T_a)/I_c$ for three different mass flow rates have been presented. The maximum efficiencies for pin fin, hemispherical protrusion and corrugated absorbers are computated as 85 %, 75 % and 65 %, 80 %, 70 % and 60 %, 75 %, 65 % and 55 % at mass flow rates of $\dot{m}1$= 0.0417, $\dot{m}2$= 0.0313 and $\dot{m}3$ = 0.0208 kg/s (Fig.6, Fig.7, and Fig.8). The data available from these figures are fitted to straight line using least squares data fitting approach. It is evident from these figures that efficiency decreases as temperature parameter increases. It implies that at higher temperature parameter the energy loss is lower. Efficiency increases at higher mass flow rate because of the fact that it changes fluid flow from laminar to turbulent region. In the present studies, maximum thermal efficiency is observed for pin fin absorber due to high rate of turbulence and minimum for corrugated absorber for least turbulence for same mass flow rate.

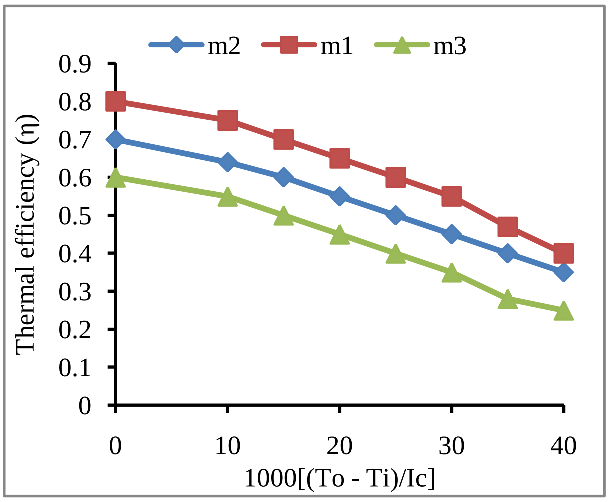

Fig. 7 Variations of collector efficiency with temperature parameter for hemispherical protrusion.

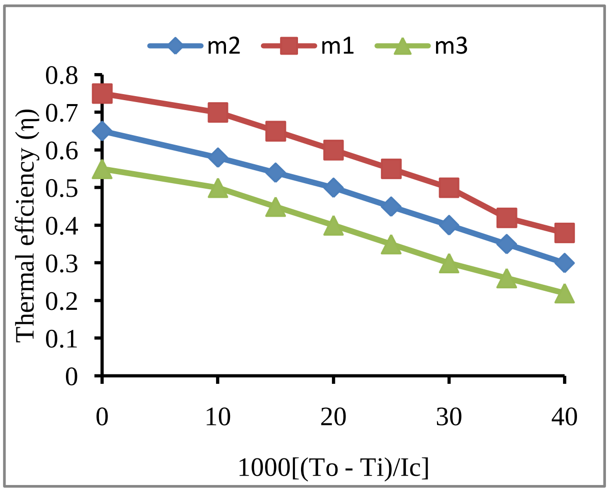

Fig. 8 Variations of collector efficiency with temperature parameter for corrugated absorber

The heat gain factors are calculated from regression analysis of above experimental data. The values of F_R, F_o, F' and U_L are calculated from slope and the intercepts of the best lines of above figures. The highest values of heat gain factors are obtained for pin fin absorber and least value for corrugated absorber (Fig.9, Fig.10 and Fig.11).

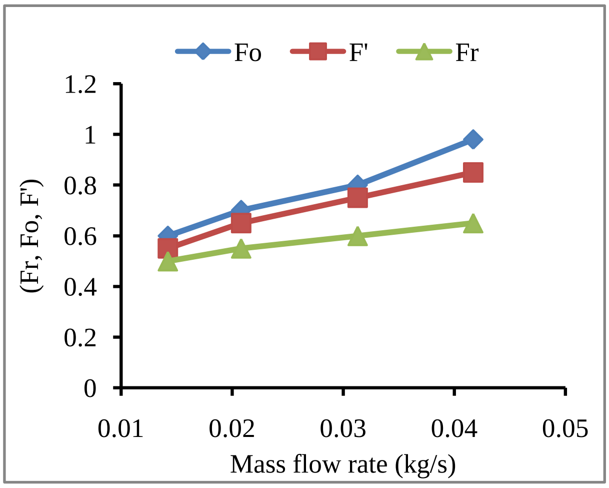

Fig.9 Heat gain factor for pin fin

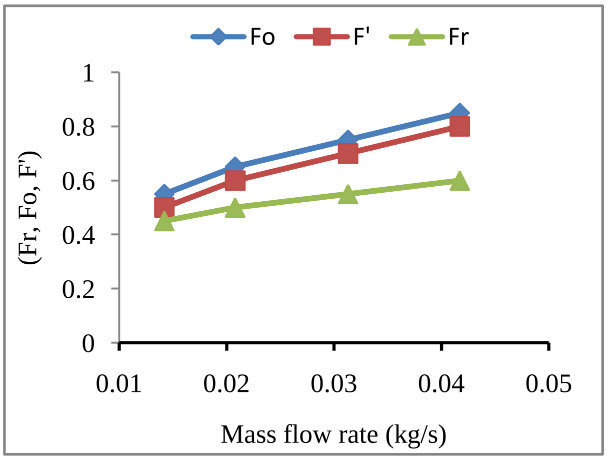

Fig.10 Heat gain factor for hemispherical absorber

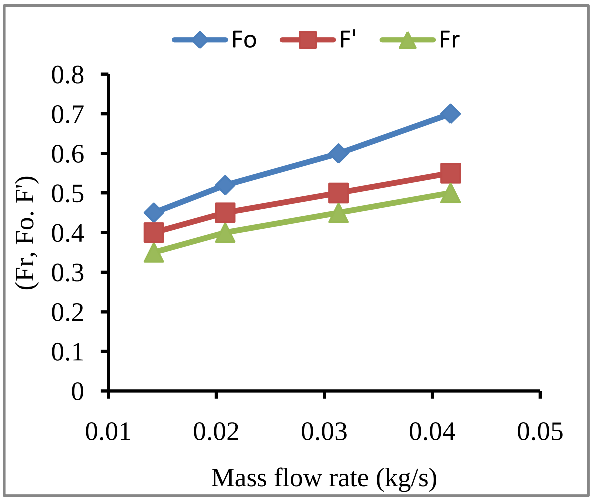

Fig.11 Heat gain factor for corrugated absorber

The F_R, F_o, F' values increase with increase in mass flow rate of air. For pin fin absorber, all the relevant factors seemed to increase substantially compared to corrugate one. The highest difference of collector heat gain factor based on exit temperature reached about 2.4 times at mass flow rate of 0.0417 kg/s. The heat loss coefficient varied from (5-20) W/m^{2}K for mass flow rate range of (0.0208-0.0417) kg/s. The minimum value was observed corresponding to pin fin absorber and maximum value for corrugated absorber. This indicates that pin fin absorber is in the best performance over hemispherical protruded and corrugated absorbers.

To study thermo hydraulic performance of three absorbers, variation of Reynolds number with Nusselt number and friction factor has been presented in Fig.12 and Fig.13. It is evident that maximum heat transfer occurs for pin fin absorber following hemispherical and corrugated absorber. However, friction loss is maximum for pin fin and minimum for corrugated absorber probably because better aerodynamic design

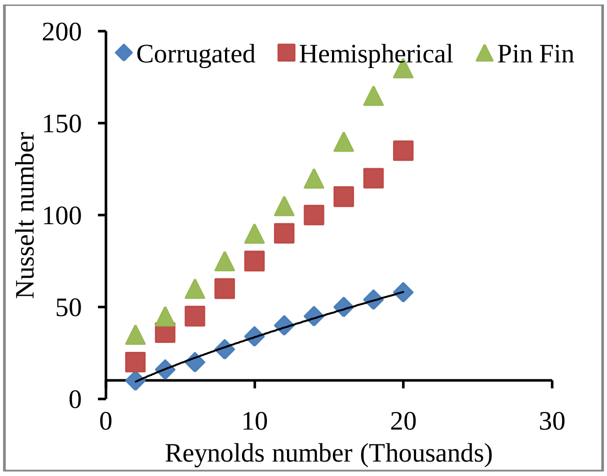

Fig.12 Variation of Reynolds number with Nusselt number

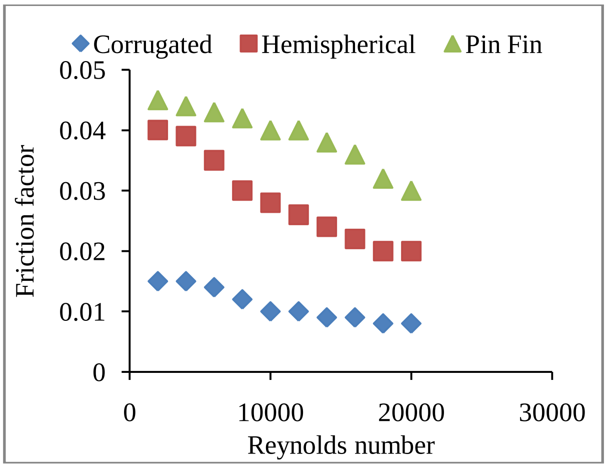

Fig.13 Variation of Reynolds number with friction factor.

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5. CONCLUSIONS

Three different solar energy absorbers (air heater) have designed in house. They are namely pin fin, corrugated and hemispherical protruded absorbers. The following conclusions have been drawn from these studies.

The efficiency of solar collector depends on various parameters such as solar radiation, surface geometry of the absorber, Reynolds number, friction factor, absorber temperature and optimal ratios of different roughness geometry parameters. The efficiency of all three solar air heater increased with increase in mass flow rate due increase turbulence and hence heat transfer. Best thermal efficiency was observed for pin fin absorber and worst for corrugated for same mass flow rate. Converse to this, frictional loss was found maximum for pin fin absorber and minimum for corrugated absorber.

Different heat removal factors were also calculated from experimental data. Maximum value of collector heat gain factor based on outlet air temperature was computed to 0.98 and minimum 0.45 for pin fin absorber at mass flow rate of 0.0417 kg/s. Similarly heat loss coefficient was minimum for pin fin and maximum for corrugated absorber.

NOMENCLATURE

Symbols

A	Area of cross section	(m^2)
A_p	Area of absorber plate	(m^2
A_{ff}	Free flow area	(m^2)
C_p	Specific heat of air	($Jkg^{-1}K^{-1}$)
C	Clearance between fin tip and the roof	mm
c	Constant= $\eta_F\ \eta_m\ \eta_{tr}\ \eta_{th}$	
d_f	diameter of pin-fin	(mm)
d	Print diameter of hemispherical protrusion	(mm)
D	Hydraulic diameter of the duct.	(m)
e	Height of roughness element.	(m)
F′	Plate efficiency factor.	
F_R	Collector heat removal factor.	
f	Friction factor.	
f_s	Friction factor for smooth passages.	
H	Height of the duct.	(m)
h	Convective heat transfer coefficient.	($Wm^{-2}K^{-1}$)
h_f	Height of pin fin.	(mm)
I	Intensity of solar radiation.	(Wm^{-2})
k	Thermal conductivity of air.	($Wm^{-1}K^{-1}$)
L_c	Length of collector.	(m)
L	Long way length between protrusions.	(mm)
m	Mass flow rate	($kg\ s^{-1}$)
Nu	Nusselt number	
N_x	No of fins along the X-direction	
P_m	Mechanical energy consumed for propelling air through collector.	(W)
ΔP	Pressure drop across collector length.	(Nm^{-2})
q_u	Useful heat gain	(W)
Re	Reynolds number	
S	Short way length between protrusions.	(m)
T_a,	Ambient temperature	(K)
T_i	Inlet air temperature	(K)
T_o	Outlet air temperature	(K)
T_p,	Plate temperature	(K)
t_{fm}	Mean fluid temperature	(K)
t_{pm}	Mean plate temperature	(K)
U	Overall heat loss coefficient	($Wm^{-2}K^{-1}$)
V	Velocity of air in solar air heater duct.	(ms^{-1})
W	Width of the solar air heater duct.	(m)
Q	Incident energy	(W)
$\dot{m}$	Mass flow rate	$kg\ s^{-1}$

Greek Symbols

τ	Transmittance
α	Absorptance
η	Efficiency
ρ	Density
β	Angle of attack

Subscripts

a	Ambient
c	Collector
f	Fin
ff	Fluid flow
fm	Fluid mean
i	Inlet
l	Loss
m	Mechanical
n	Hydraulic
o	Outlet
p	Plate
pm	Plate mean
s	Smooth
u	Useful
b	Back
s	Side

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t	Top
cl	Collector loss

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